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2. Patent application number *(The Patent Office will fill in this part)* — 0315247.7 — 30 JUN 2003

3. Full name, address and postcode of the or of each applicant *(underline all surnames)*

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Patents ADP number *(if you know it)* — 8809689001

If the applicant is a corporate body, give the country/state of its incorporation

4. Title of the invention — IMPROVEMENTS IN OR RELATING TO FLUID FLOWS AND JETS

5. Name of your agent *(if you have one)* — BROOKES BATCHELLOR LLP

"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*

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Improvements In Or Relating To Fluid Flows And Jets

The present invention relates to improvements in or relating to fluid flows and jets. In particular it relates to a flared nozzle for controlled expansion of swirling fluid flows and jets

A device is presented, which is designed to enable controlled expansion of swirling fluid flows and, in particular, swirling fluid jets. A swirling fluid jet is defined as any fluid with components of axial and tangential (swirl) velocity that emerges from a circular duct into an unconfined ambient. An ambient is any like fluid to that comprising the jet. The purpose of expanding such a swirling flow, is two-fold:

- To exploit certain flow phenomena associated with a swirling flow or jet; in particular the pre-breakdown (precessional) and post-breakdown (re-circulation) flow behaviour.
- To take advantage of the increase in static pressure associated with a just-broken swirling flow or jet. Pressure recovery can then be used: for example, for reducing energy wastage in the exhaust flows from roto-dynamic machines.

Typically, the fluid is water. However, it may also be gas (air) if the expansion process takes place substantially at atmospheric pressure.

A conventional conical diffuser is a device, whose (sole) function is to induce a uniform and uni-directional cross-sectional area expansion of a (non-swirling) fluid stream, thereby achieving a reduction in velocity and an increase in static pressure. However, conventional conical diffusers tend to be very long relative to their width, because to avoid significant losses the cone angle has to be less than 10^0 (see, for example, Massey 1998, Figure 7.10). Above a cone angle of about 12^0, fluid begins to separate from the wall and conventional conical diffusers, thereafter, rapidly become very inefficient. This means that efficient pressure recovery, comes at a premium in terms of diffuser size and weight, and cost of diffuser fabrication. Additionally, there are no beneficial characteristics, in terms of unusual jet behaviour, associated with an expanded axial (non-swirling) flow.

However, where the benefits of pressure recovery are large and space permits, diffusers of conventional design are often used. Examples include the outlets from wind tunnels and water tunnels; the volutes of centrifugal pumps; the draft tubes of water turbines and the outlets from jet pumps. In these and other applications that do not currently employ diffusers, there are potential benefits to the use of the herein-described invention. The potential uses or the device, however, are not limited to replacing conventional conical diffusers, as will become evident from later discussion.

According to the present invention, there is provided, in one aspect, a method of controlling the expansion of swirling fluid flows and jets from a duct. The method comprises providing an outlet of the duct with a flared nozzle, the nozzle having an inlet, an outlet and an intermediate profiled body having pre-determined dimensional characteristics.

In a second aspect, the present invention provides a nozzle for a fluid duct, the nozzle ~~having an inlet and outlet and an intermediate profiled body having pre-determined~~ dimensional characteristics.

The present invention also relates to the use of the method and nozzle of the present invention in producing fluid flows and jets having swirl characteristics intended for specific tasks. In one embodiment, the present invention provides the use of the nozzle of the present invention to produce a fluid flow or jet having a Jet Swirl Number of at least about 2, preferably about 4. Such flows are useful in combustion apparatus and seabed excavation apparatus.

In an alternative embodiment, the present invention provides the use of the nozzle of the present invention to produce a fluid flow or jet having a Jet Swirl Number from 0.5 to 1.0, preferably from 0.7 to 0.85. Such flows are useful for providing propulsion.

The present invention can be likened to a (wide-angle) conical diffuser. However, it differs physically, in that the internal angle increases lengthways from 0^0 to 180^0, and the length-to-width ratio is significantly smaller. It also differs in terms of operating principle in that it is not designed, specifically, to reduce the axial velocity, uniformly and uni-directionally, across the nozzle diameter; but rather to re-distribute axial flow momentum within the jet in such a way as to produce certain desirable flow patterns. One such flow pattern happens to include a uniform, uni-directional, axial velocity re-distribution.

Re-distribution of axial flow momentum by means of the present invention relies, implicitly, on the swirl (tangential velocity) content of the inlet flow. The invention exploits the natural ability of swirl to rapidly convert axial flow into radial flow, and visa versa. Note that radial flow may be outwards (away from) or inwards (towards) the central axis of the flow. During the initial expansion of the jet it is outwards, but it may become inwards again, depending on the subsequent downstream jet behaviour. The initially expanded jet thus has a higher (outward) radial velocity flux and a lower axial velocity flux. Since the swirl velocity flux remains essentially constant, by implication, there is a net increase in the swirl-to-axial velocity flux ratio (i.e. an increase in Swirl Number, see below). By controlling the amount of expansion through the nozzle, the axial and radial velocity fluxes can be manipulated in such a way as to produce predictable jet behaviour.

To achieve optimum expansion, the internal profile of the flared nozzle is matched, precisely, to the swirl content of the inlet flow. Whilst an existing swirling flow is advantageous it is not essential, since swirl can be readily imparted to the inlet flow.

Figure 1 shows the basic features of the new flared nozzle (1), which comprises but a single component. This is tubular in form with an inlet (2), a profiled body (3) and an outlet (4). When in use, the nozzle would be attached, co-axially, by means of inlet (2) to a duct emitting a swirling flow.

If the primary flow is not swirling, or possess too little swirl, a fore-nozzle duct (5), incorporating a swirl generator (6), may be interposed between the flared nozzle and the primary flow duct. Swirl generator (6) may comprise any means that imparts a

measured amount of tangential velocity (swirl) to the flow. As shown in Figure 1 it ~~consists of a series of static, radially-disposed, angled vanes, designed to convert part~~ of the axial flow stream into swirl.

Flared nozzle (1) is designed to operate with fully turbulent inlet flows having Swirl Numbers typically in the range 0.2 to 2.0. Swirl Number is defined in Appendix A. Many practical flows have Swirl Numbers in this range, or simple static swirl generators may be used to create such a swirling flow. Provided the flow is turbulent, the device is relatively insensitive to the Reynolds number of the inlet flow (see Appendix A for definition). The nozzle can achieve a maximum expansion, in terms of inlet-to-outlet area ratio, of 4 times. This is equivalent to a 2 times diametral expansion.

To achieve optimum expansion of a swirling flow through such a nozzle, the profile of the nozzle has to be elliptical (parabolic) in form. Figure 2 shows such a profile, and illustrates a means for simple geometrical construction of an elliptical profile. An elliptical profile is fundamental to the design and operation of the present flared nozzle.

The dimensional characteristics of the flared nozzle are determined, step-wise, according to a set of rules, which are set out as follows.

Step 1

The Area Expansion Ratio of the nozzle: that is ratio of outlet-to-inlet areas, is first determined. This defines the change (increase) in Swirl Number through the nozzle.

Area Expansion Ratio (AER), is defined as:

$$AER = \frac{a_2}{a_1} \qquad \text{(Rule 1.)}$$

Where: a_1 = cross-sectional area of inlet
a_2 = cross-sectional area of outlet

Change in Swirl Number through the nozzle is equal to the AER of the nozzle. Note that AER can be up to 4.

Step 2

Area Expansion Ratio then allows the step height of the nozzle to be determined. Step height (H) is defined as:

$$H = (d_2 - d_1) \div 2 \qquad \text{(Rule 2.)}$$

Where: d_1 = diameter of inlet
d_2 = diameter of outlet

Step 3

Nozzle length is then determined. Where nozzle length (L) is defined as:

$$L = 2H \div \text{inlet Swirl Number} \qquad \text{(Rule 3.)}$$

Step 4

The appropriate elliptical curve can then be drawn using the previously determined step height and nozzle length dimensions as orthogonal axes. Any elliptical curve-drawing method may be used; the one shown in Figure 2 uses a ruler and length of thread.

In Figure 3 a number of elliptical profiles are plotted, to illustrate some key features, keeping either a fixed nozzle diameter, step height and AER, but varying the inlet Swirl Number (Figure 3a), or a fixed nozzle diameter and inlet Swirl Number, but varying the AER (Figure 3b). Referring to Figure 3a: note that as the inlet Swirl Number decreases, the nozzle length (for optimum expansion) increases, rapidly so at low inlet Swirl Numbers. Note also, that at an inlet Swirl Number of 2 the nozzle becomes uniquely circular in profile, while at still higher inlet Swirl Numbers the nozzle profile becomes elliptical again, but with the step height being greater than the length (axes reversed). With fixed nozzle diameter and inlet Swirl Number (Figure 3b) both nozzle length and nozzle outlet diameter increase with increasing AER.

The rapid increase in nozzle length at low inlet Swirl Numbers, for a fixed step height, is because nozzle length is inversely proportional to inlet Swirl Number (parabolic function). The product of step height and nozzle length, on the other hand, is directly proportional to AER (linear function). Note that at very low Swirl Numbers the nozzle length becomes very large, and comparable to that of conventional conical diffusers. Since a Swirl Number of 0.05 can be taken as a practical lower limit for self-sustaining swirl motion in pipes (below this swirl damps out very quickly), a step height to nozzle length ratio of 1:40 can be seen as the point where the flared nozzle and conventional conical diffusers overlap.

Area Expansion Ratio and inlet Swirl Number, together, define unique flared nozzle geometrical characteristics. This is shown in Figure 4, where optimum AER and inlet Swirl Number are plotted in AER/nozzle-geometry space, non-dimensionalised by inlet Swirl Number. Figure 4 is, in effect, a graphical form of Rules 1.) to 3.), and can be used to derive nozzle geometry for the range of AER and Swirl Number values plotted. Figure 4 illustrates another key feature, which is that for each inlet Swirl Number a flow can be expanded in optimum fashion to a maximum of AER = 4, since the latter marks an asymptotic boundary on the graph.

Published experiments on expanded swirling flows in closed pipes (Dellenback 1988, Guo et al 1999) provide a basis for understanding the present invention and the effects of different Swirl Numbers, as they manifest themselves in a swirling fluid flow or jet. Previous publications do not, however, recognise the significance of an elliptical profile in providing a natural (optimum) bounding surface to the expanding flow.

To appreciate the potential uses of this device it is necessary to have a basic knowledge of the flow mechanics and behavioural characteristics associated with fully turbulent swirling flows and jets.

~~Table 1 (incorporating published data from Dellenback et al 1988 and Guo et al 2001)~~ shows how an expanded swirling jet will behave based on its (implied) Jet Swirl Number. Implied Jet Swirl Number (hereinafter referred to, simply, as Jet Swirl Number) has been derived from the above referenced data, by multiplying the inlet Swirl Number by the appropriate Area Expansion Ratio. Note that Jet Swirl Number is a way of quantifying swirling jets for the purpose of rationalising their behaviour. For completeness, the behaviour of a non-swirling jet is also included.

Note also that the steady axial and peripheral disturbances, which generally accompany the varying jet topologies (as described in Table 1), are those that would tend to occur, more particularly, in confined flows. In confined (i.e. expanded pipe) flows, outward coning of the jet cannot occur, and is replaced by smearing of the flow against the pipe wall.

Table 1.

Jet Swirl Number	**Jet Behaviour**
0	Jet is axi-symmetric. Reynolds boundary stresses are negative so jet entrains ambient fluid as it expands, width-ways, at an included angle of 20^0-25^0.
0-0.5	Jet becomes increasingly columnar (straight-sided), Reynolds boundary stresses reduce and entrainment diminishes. Precession (spiral rotation) about the axis takes place, although the axis of precession departs only slightly from the main jet axis. The direction of rotation of the precession is opposite to that of the primary swirl.
0.5	Precession stops. Reynolds boundary stresses go to zero and jet is straight-sided.
0.5-1.5	Precession starts again, but with rotation in the same direction as the primary swirl. Speed of precession rotation increases linearly with increase in Swirl Number. Axis of precession departs increasingly from the jet axis to produce a straight-sided annular conical jet. Maximum cone angle is 60^0, corresponding to the highest Swirl Number. Reynolds stresses are negative, so entrainment takes place on both the outer and inner conical surfaces. Flow towards the inner surface is essentially a counter-flow, which takes place uniformly across the width of the jet. By implication, the apex of the cone is marked by a steady out-of-balance inducing disturbance, which may be located axially (lop-sided spherical re-circulation "bubble") or peripherally (partial or lop-sided ring vortex), or a combination of both. The disturbance(s) grow(s) with increase in cone angle.
1.5-2.0	Jet experiences breakdown, with transformation into a uniform flow annular (axi-symmetric) jet, with the same 60^0-cone angle. Axial steady disturbance (spherical breakdown "bubble") becomes symmetrical and with a diameter greater than the jet vortex core, or equal to the jet vortex core if peripheral steady disturbance (symmetrical ring vortex) is present.
2.0-4.0	Jet form remains essentially as above, but re-circulation "bubble" becomes elongate and develops an extended axial counter-flow tail. Axial counter-flow tail develops into a swirling tube-like flow (c.f.

	tornado) with increasing Swirl Number, and is accompanied by a strong centrifuging effect at the head of the counter-flow stream. Between the outer annular conical jet and the axial counter-flow vortex, the flow is essentially re-circulatory. Re-circulation is driven by the outer conical jet flow along a pronounced shear surface, which separates the two flow regions. This shear surface appears to develop secondary oscillations (eddies). Centrifuge effects also contributes to re-circulation flow at higher Swirl Numbers.

While the changes in jet form described in Table 1 are essentially part of a continuum, a Swirl Number of 1.5 (or to be exact, $1.414 \equiv \sqrt{2}$) can be seen as marking a critical threshold in terms of internal flow dynamics (Benjamin 1962). Up to this point, the primary jet flow remains essentially intact, albeit departing significantly from the jet axis in the form of a spiral precessing jet. At the critical threshold, the swirl effectively overcomes the axial flow and the jet undergoes a sudden transformation (breakdown); changing from an asymmetric single-cell flow to an axi-symmetric two-cell flow, with the development of an axial re-circulation flow. This transformation is analogous to a hydraulic jump (in surface flows) or normal shock (in compressible flows). With increasing Swirl Number above the critical value, the jet is able to cone out at a wider angle, and a progressively stronger counter-flow develops along the axis.

This critical state breakdown condition is associated with complete blocking of the primary swirling jet core by the steady axial disturbance. Note that the swirling jet core is the axial forced-vortex portion of the jet (see Appendix A for definition of forced vortex). The steady axial disturbance can be seen as applying a pressure against the flow (see, for instance: Marshall 1993 and Darmofil et al 2001). The effect is analogous to a ball being held against the outlet stream from a pipe, where the ball is slightly larger than the diameter of the pipe. The jet is deflected uniformly to form a conically splayed jet. Up to this point, the steady axial disturbance (the ball) has been smaller than the jet core (the pipe) and has tended to oscillate, causing the jet to splay but in a spiral fashion (c.f. a garden sprinkler). With increasing Swirl Number beyond the breaking point, the creation of an axial counter-flow stream reinforces the axial blocking effect and allows the development of a secondary re-circulation flow pattern. The general form of a broken, high-swirl, re-circulating, jet is shown in Figure 8.

Up to the point of breaking of the jet, the role of the steady axial disturbance can be replaced by a steady peripheral disturbance. Beyond the breaking point, a steady peripheral disturbance can replace the need for the steady axial disturbance to grow in size. The flared nozzle can thus be seen as supplanting the role of the steady peripheral disturbance, both in advance of and following breakdown.

By means of the flared nozzle, the sequence of stages described in Table 1 can be induced in a swirling flow starting from any inlet Swirl Number, simply by selecting an appropriate Area Expansion Ratio and nozzle geometry; provided that the increase in Swirl Number does not exceed 4. It should be appreciated that the induced flow pattern develops inside the nozzle.

A number of potential applications for the device will now be briefly described, ~~covering a range of inlet and Jet Swirl Numbers. The examples also serve to illustrate~~ application of the flared nozzle design rules.

By expanding any lesser Swirl Number flow to give a Jet Swirl Number of greater than 0.5 but less than 1.0, a conical annular spiralling jet, with a cone angle up to about 45^0 can be produced. In such a conical jet, axial flow momentum is coupled into the ambient fluid not only over a larger outer surface (compared to a columnar jet), but over an inner surface also.

Rapid coupling of jet energy into the ambient fluid provides the means for enhancing (jet) thrust in rotational-based (i.e. propeller) propulsion systems. It is particularly appropriate for slow-speed vessel operation and is thought to be the principle on which so-called thrust-efficient (i.e. high-swirl generating) propellers operate. However, the cone angle has to be kept relatively small because the flow towards the inner cone surface is essentially a counter-flow, and can induce negative thrust at large cone angles. Also as vessel speed increases relative to jet flow speed this counter-flow creates an increasing amount of drag.

It is worth noting that in the slipstream of a normal ship's propeller, as it decelerates downstream (i.e. with increasing Swirl Number) this spiral coning effect can be seen (see, for instance, Stella et al 2000). The flared nozzle, by creating a conical spiral precessing jet, thus provides a means for foreshortening the slipstream development (ageing) process. By increasing the rate of axial deceleration and thus attenuating the length and of the slipstream, the flared nozzle also enables vessels to operate more effectively in enclosed situations, with better manoeuvring and less propeller-wash damage to harbour structures.

Normal ships' propellers are generally designed for cruising-speed operation, at a Jet Swirl Number of about 0.3, and become increasingly inefficient when operating at slower speed, as the Jet Swirl Number rises to about 0.5. This increase in Jet Swirl Number results from the attendant reduction in axial flow through the propeller at slower vessel speed (lower advance coefficient). By incorporating a conventional high-speed propeller into a duct, fitted with a flared nozzle, slow-speed thrust efficiency can be increased, by raising the Jet Swirl Number above 0.5.

By way of illustration, assume the inlet (i.e. propeller-generated) Swirl Number is 0.5 (which is typical of ships' propellers with a constant pitch/diameter ratio of 1.0, at zero advance speed). Assume also that the intended outlet (Jet) Swirl Number is 0.7 (equivalent to a very high-swirl propeller); the Area Expansion Ratio is thus 1.4. The appropriate flared nozzle would need to have an outlet diameter 1.18 times the propeller duct (i.e. a step height of 0.9) and a nozzle length of 3.6 times the step height (assuming a propeller diameter of 1).

The most basic form of a vessel propulsion system incorporating the flared nozzle is shown in Figure 5a, with various alternative embodiments being shown in Figures 5b-f. For each application, the flared nozzle would be matched to the Swirl Number of the propeller at the particular (slow) vessel speed it was intended to enhance (i.e. the Nozzle Design Speed). In the case of forward propulsion systems, the influence of the flared nozzle will reduce (i.e. the cone angle will reduce) as forward vessel speed

increases, thus allowing the propeller to attain its optimum design speed efficiency. The propeller/duct/flared nozzle combination can be seen as working, in effect, like an automatic two-speed gearbox.

In the case of lateral propulsion systems (Figure 5f), where back-to-back flared nozzles would provide the transition between the thruster-tunnel (duct) and the outer hull of the vessel, only slow speed operation is required. In this case, the propeller would have a zero advance speed Swirl Number of about 0.5, and the flared nozzle would be chosen to give an induced (Jet) Swirl Number of, perhaps, 0.7-0.85.

Note that the (constant pitch) propeller/duct/flared nozzle arrangement described can achieve higher thrust efficiency than a thrust-efficient propeller in a straight duct. This is because the thrust-efficient (high-swirl) propeller inevitably sacrifices some axial flow generation, for swirl generation.

Once broken, jet behaviour changes completely and the jet becomes potentially useful for a different set of applications, depending on its breakdown state.

Initially, in the just-broken condition, the jet can be used for pressure recovery purposes. This is because the jet flow is axi-symmetric and largely uni-directional; re-circulation being confined to the spherical bubble. Although additional turbulence is generated, the bubble (in the case of flared nozzle operation) remains relatively small and does not penetrate the inlet duct, so there is no blocking of the primary flow. Inward re-distribution of axial flow momentum takes place very rapidly downstream of the bubble (typically within 1 to 2 nozzle outlet diameters). However, to prevent downstream contraction of the jet an equivalent length of after-duct (7) is required, as shown in Figure 6.

Given the higher Jet Swirl Number (1.5-2.0), it is appropriate to use a higher inlet Swirl Number. Assume, for instance, an inlet Swirl Number of 0.5, which would allow a three- to four-fold increase in pressure recovery (AER = 3 to 4). To achieve a jet Swirl Number of 2, from an inlet Swirl Number of 0.5, would mean a nozzle step height of 0.5 and a nozzle length of 1.5 (assuming an inlet diameter of 1). An after-duct twice the length of the outlet diameter of the nozzle would also be used. The particular applications, in this instance, might include being used in place of the existing draft tubes of reaction turbines and the volutes/diffusers of axial and mixed flow pumps or, alternatively, being incorporated into the downstream pipe-work from these machines (non-jet application).

To further increase the efficiency of the device for this purpose, the spherical bubble and associated wake-field, can be supplanted by an appropriately profiled, smooth-surfaced, after-body (8), as shown in Figure 6. This can be either supported from the nozzle by small-diameter struts (9, in Figure 6a) or tethered axially from a central point in the inlet duct or flared nozzle (10, in Figure 6b) by means of a rigid (11) or flexible (12) connection. In the latter case, the after-body would be of light-weight composition, to enable it to rapidly adopts an axial position in response to flow through the nozzle.

With increasing Jet Swirl Number above 2, a progressively greater amount of axial counter-flow and re-circulation takes place within the body of the jet, the jet also

splays out at a progressively wider angle due to centrifuging at the head of the ~~counter-flow stream. Additionally, there is more internal shear, and so greater~~ turbulence within the jet. Applications which currently make use of these characteristics, include: swirl combustors as used in gas turbine engines (Shin 1993), and gas- and oil-fired boilers; spray dryers (Guo et al 2001), and a novel seabed excavation device, as discussed more fully later.

In the case of combustion devices, the important characteristics of the jet (i.e. flame) are: high turbulence, to create good fuel/air mixing; flame stability/length, and ingestion of hot gas to pre-heat the fuel/air mixture. The flame has to stay lighted and stable and so the appropriate length of flame depends to some extent on whether it is operating in a cross flow. To increase turbulence (for mixing purposes), advance gas turbine combustors often use co-axial counter-swirling jets. Ingestion of hot gas is achieved by the axial counter-flow effect.

Notwithstanding the complex requirements associated with different types of combustion process, the ability to be able to pre-determine and control the characteristics of the jet by means of the flared nozzle is considered highly relevant to the field of combustion technology.

As has already been mentioned, above a Jet Swirl Number of 1.5 a flow will break naturally as it emerges from a duct, without any additional help from an expansion nozzle. However, a flared nozzle of the present design may still be useful in order to control the breakdown process. Without such a nozzle, highly swirled flows issuing from a duct (such as from cyclone separators) can be very unstable and develop pronounced out-of-balance effects. This can lead to vibration and noise (Yazdabadi and Griffiths 1993). The counter-flow stream may also penetrate and partially block the duct entrance, leading to loss of efficiency (Griffiths, et al 1998). In this instance, a longer flared nozzle may be selected, which is specifically designed to under-expand the flow. The jet thus experiences a lesser degree of breakdown than would occur without the flared nozzle. Similarly, the flared nozzle may be incorporated into pipework to control vibration and noise (non-jet application).

The novel seabed excavation device, whose development led to the development and realisation of the flared nozzle concept, will now be described in more detail. This particular device utilises the strong axial counter-flow and well-developed re-circulation flow pattern generated by a highly swirled broken jet (Jet Swirl Number of 4), to both erode and lift bed material into suspension. Material transported upwards in the axial counter-flow stream is flung out sideways (centrifuge effect) into the radially deflected axial flow; being transported away as this flow first descends to and then spreads out across the bed. Excavation and movement of sediment reach an optimum with a jet Swirl Number of 4. This is because:

1. The jet splays out at the widest angle, giving the maximum impingement footprint area.
2. The counter-flow is strongest, which means that a strong suction is applied to the bed (causing fluidisation) and the maximum amount of material can be lifted upwards in the axial counter-flow.
3. Because of the high density of the re-circulation flow stream (due to the concentration of suspended sediment) centrifugal action is augmented at the head

of the counter-flow causing the whole jet to splay out more widely (jet becomes umbrella-shaped), with further increase in the size of the impingement footprint. A similar centrifuging effect (although in a confined fashion) is seen in rotating pipe heat exchangers (Shtern et al 2001).

4. In the presence of frictional (i.e. non-cohesive) materials, a strong centripetal flow (Eckman layer flow) takes place across the bed within the impingement footprint region. Because this near-bed flow has increased turbulence, as well as viscosity (due to fine sediment in suspension), it is able to actively erode the bed and transport a wide range of sediment particle-sizes inwards, in suspension, towards the axial counter-flow zone.
5. Because the material lofted in the counter-flow is entrained directly into the high velocity deflected axial flow stream, very little material escapes from the umbrella-shaped envelope of the jet. The process, therefore, does not cause an increase in the amount of suspended sediment in the water column.
6. Because the peripheral jet flow stream meets the bed at a shallow angle the flow continues across the bed without significant loss of momentum, and the high concentration of sediment particles means that this near-bed flow will propagate as a density current over long distances.
7. In addition, at the height above the bed at which the device is typically operated, the boundary Reynolds stress in the deflected outer part of the jet are nearly neutral. The flow can thus propagate across the bed without significant interaction with the overlying water. This is in contrast to the wall jet flow created by impingement of a normal turbulent round jet.

The whole process is, therefore, highly efficient and can achieve a very high rate of excavation and sediment movement.

In addition, the device can be used to excavate virtually any soil material, including very stiff clays, which are otherwise very difficult to excavate by means of conventional water-jetting techniques. This enhanced excavation capability derives from the fact that with cohesive (i.e. low friction) bed materials a strong suction develops as the nozzle is brought closer to the bed. This is due to pressure decay on the swirl axis (c.f. a grounded tornado). Most cohesive soil materials are weakest in tension, compared to compression and shear.

Note that the process also provides an effective means for the cleaning of vessel hulls, as discussed more fully in 0227016.3.

One form of the device is a ducted-propeller, as shown in Figure 7. This comprises a duct (13), with an inlet (14) and an outlet (15). A motor (16), placed co-axially in the duct, drives a propeller (17), which is located close to the outlet. The device uses a large-bladed, high-swirl, propeller, designed to create a (non-expanded) jet Swirl Number of 0.6. Note that this is about the maximum Swirl Number that can be readily obtained from a conventional ship's propeller. However, as the device (even without the nozzle fitted) is brought within impingement distance of the bed, the jet Swirl Number increases due to reaction with the bed causing a reduction in axial velocity. This reduction in axial velocity (and associated increase in Jet Swirl Number) is primarily bed-distance related, but it also depends on the nature of the bed material. For instance, with smooth clay beds a rapid increase in Swirl Number occurs, which can make the jet prone to spontaneous breakdown.

During operation with the flared nozzle, an appropriate impingement distance is, therefore, chosen to give a Jet Swirl Number of about 1. The flared nozzle (18), which may be easily attached or detached by means of mating flanges (19), is designed to increase the jet Swirl Number to 4.

An alternative means for increasing the Swirl Number of the primary jet, to give a constant (i.e. non-bed dependent) Swirl Number of 1, is to place a disc (20) co-axially in front of the propeller. This has the effect of blocking the axial flow through the middle part of the propeller, so that swirl alone is created in this region. The disc can be seen as supplanting the role of the steady axial disturbance, described earlier, which would typically accompany a jet with a Swirl Number of 1. The diameter of the disc has to be carefully chosen in relation to the diameter of the swirling jet core, but is typically about 2/3rd the diameter of the propeller (1/4 the propeller duct area). By means of the disc, operation of the flared nozzle becomes independent of the bed, both in terms of distance and nature of bed material.

Note that the disc works in four ways:

- It cuts out a portion of the total flow in a region where the local Swirl Number is, in any event, relatively low, thus effectively enhancing the higher Swirl Number outer flow.
- Within its ambit it entirely cuts out axial flow and produces only swirl.
- The resulting increase in near-axis swirl generates a centrifuge (outward radial) force, which causes the marginal axial flow to cone out as it leaves the duct. The induced radial flow velocity (created at the expense of axial flow velocity) further increases the Swirl Number of the outer flow.
- The centrifuge effect also enhances both the re-circulation flow-field and the axial counter-flow in the body of the jet.

Outward coning of the (now) annular primary jet provides a means, in its own right (i.e. without the flared nozzle), for enhanced excavation, as discussed in 0227016.3.

The form of the jet created with the flared nozzle fitted, both as a free jet and as an impinging jet, is shown in Figures 8a and 8b.

A second (smaller) embodiment of the seabed excavation device is essentially the arrangement shown in Figure 1. In this instance, instead of a propeller being used to both drive the axial fluid flow and create swirl, a separate pumped source of fluid is used and swirl is imparted to the flow (before it expands through the flared nozzle) by means of a fore-duct static swirl generator. The static swirl generator would typically be configured to create an inlet flow Swirl Number of 1, with the flared nozzle raising this to a Jet Swirl Number of 4. The behavioural characteristics of the jet are thus as described for the propeller excavation device. The means for deployment and uses of this static swirl excavator device are described in 0227016.3.

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APPENDIX A

Note the following definitions and descriptions are complied from standard texts.

Swirl Number

Swirl Number is a non-dimensional, device-independent measure of the ratio of axial fluxes of swirl and linear (axial) momentum in a flow, divided by a characteristic radius.

Swirl Number (S), is defined as:

$$S = \frac{1}{R}\frac{\int_0^R r^2 UV\, dr}{\int_0 rU^2\, dr}$$

Where: R = inlet radius
r = radius of measurement
U = axial velocity
V = tangential velocity (swirl)

Reynolds Number

Reynolds number is a non-dimensional, device-independent measure of the ratio of inertial and viscous forces in a flow, multiplied by a characteristic diameter.

Reynolds number (Re), is defined as:

$$Re = \frac{\rho D u}{\mu}$$

Where: D = inlet diameter
ρ = fluid density
u = mean axial velocity
μ = fluid viscosity

Reynolds Boundary Stress

Reynolds boundary stress is a shear stress that occurs along the boundary between two fluids (typically one moving and the other stationary) which results in a momentum transfer between the two fluids. The stress is a result of the time averaged, fluctuating, components of velocity (axial and radial) within the flow, which may be positive or negative. If these two components are in-phase, the boundary stress is negative, if they are out-of-phase the boundary stress is positive. A negative boundary stress results in an inward transfer of momentum into the moving fluid (entrainment); a positive boundary stress results in an outward transfer of momentum from the moving fluid (detrainment).

Reynolds boundary stress (τ_R), is defined as:

$$\tau_R = \underline{\text{Force}} = -\rho u'v'$$

Area

Where: τ_R, u' and v' are time-averaged components
ρ = fluid density
u' = fluctuating component of axial velocity
v' = fluctuating component of radial velocity

Vortex or Swirling Flow Core

The primary swirling flows to which the present specification refers can also be referred to as vortex flows. Vortex flows can be grouped into either forced-vortex flows: in which the tangential (swirl) velocity is zero at the axis and a maximum at the periphery; or free-vortex flows: in which the peripheral velocity is zero and the axial velocity is theoretically infinite.

Because most mechanical swirl generators are essentially forced-vortex generators, a ducted swirling flow from such a device (as described herein) will tend to have an outer part, which behaves as a free-vortex, and an inner part, which behaves as a forced-vortex.

The core is essentially the forced-vortex part of the flow and represents the diameter at which the tangential velocity is a maximum. In the case of a propeller-generated swirling flow, the core extends over virtually the whole diameter of the propeller. It is not to be confused with the axial hub vortex (in the case of propeller-generated swirling flows), which represents the combined (rolled-up) viscous boundary layer shed from the propeller blade surfaces.

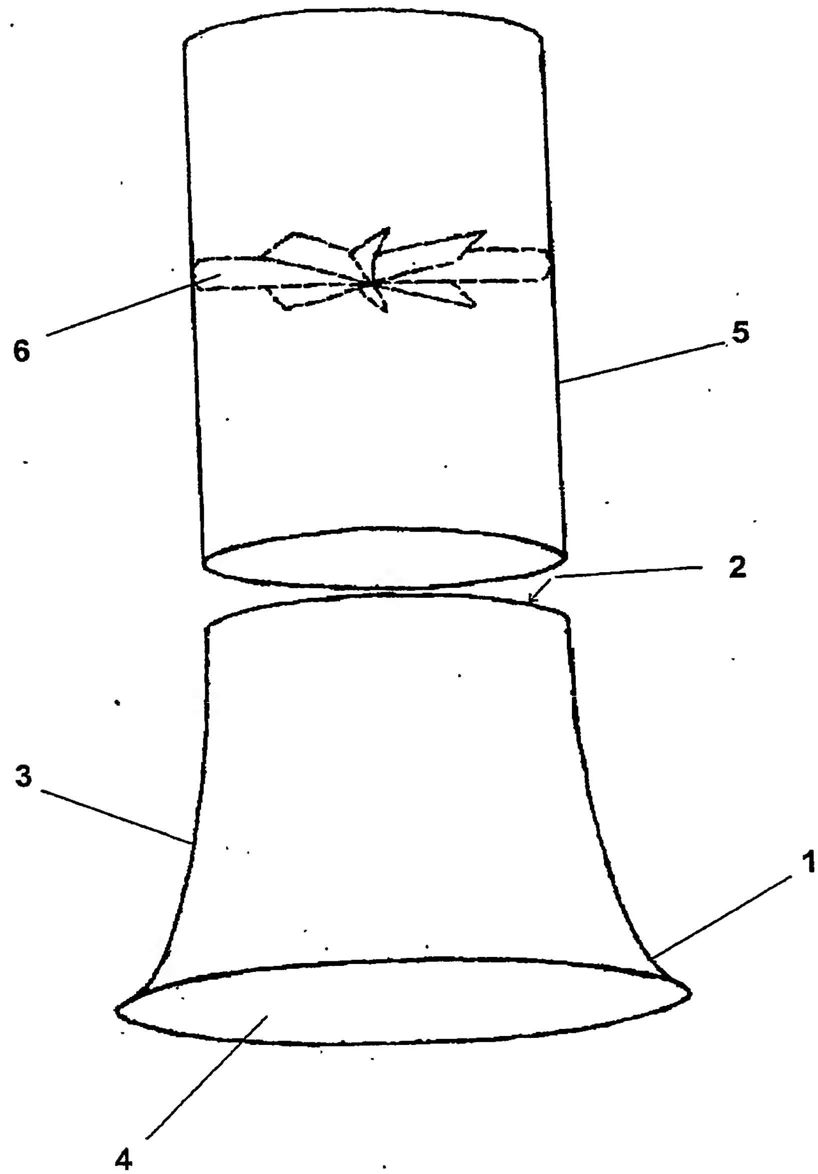


Figure 1

Step 4 - Elliptical curve drawing

Separation Distance $= \sqrt{L^2 - H^2} \times 2$

String Length $= 2 \times L$

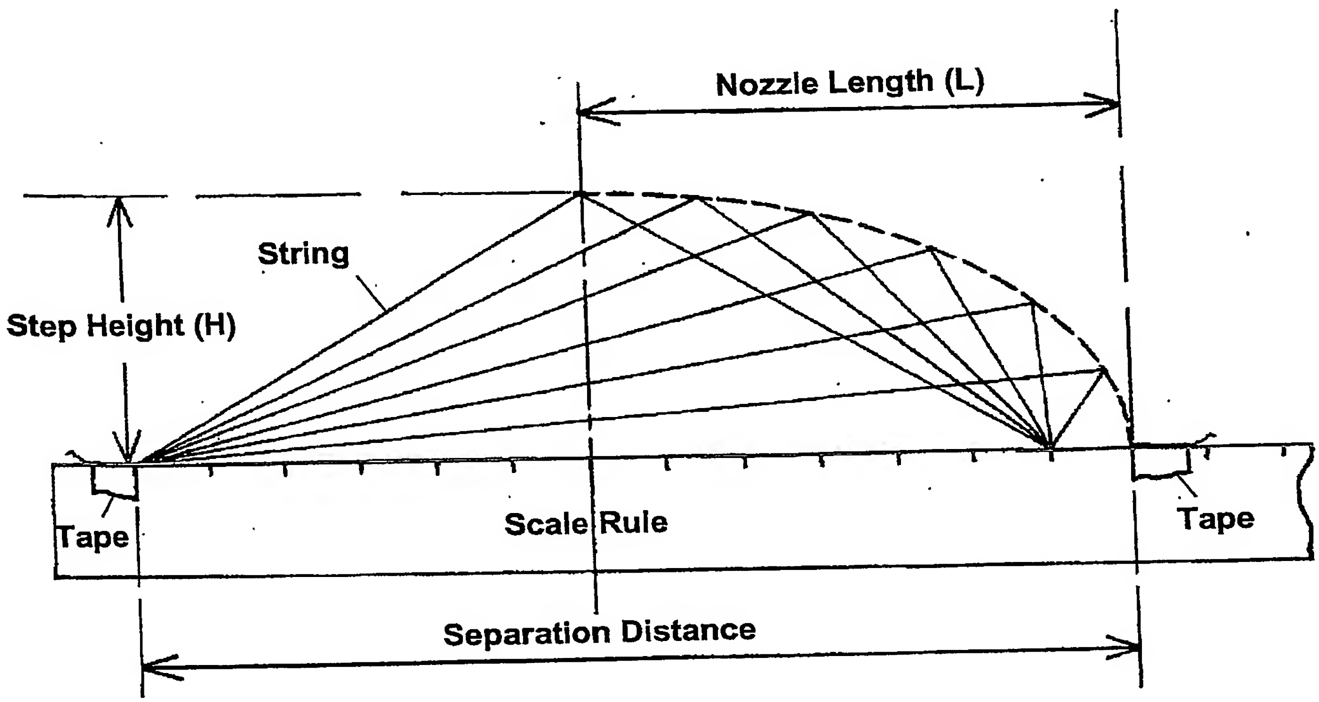
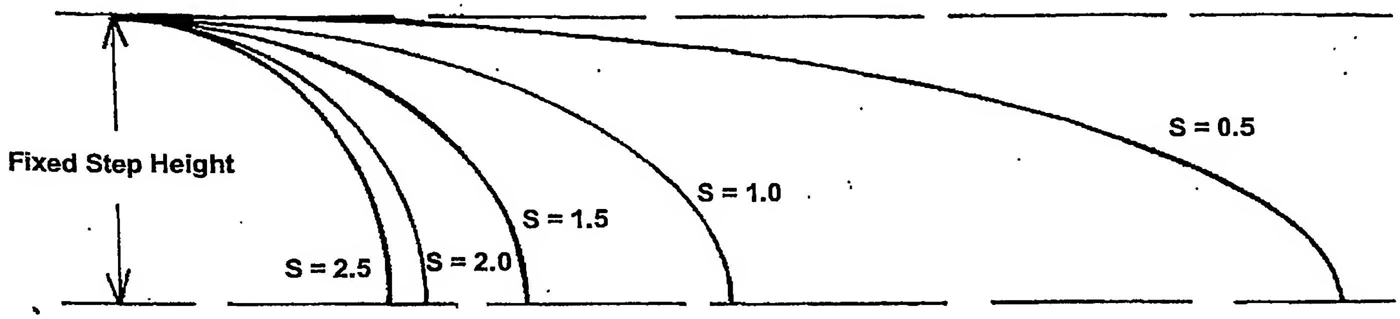
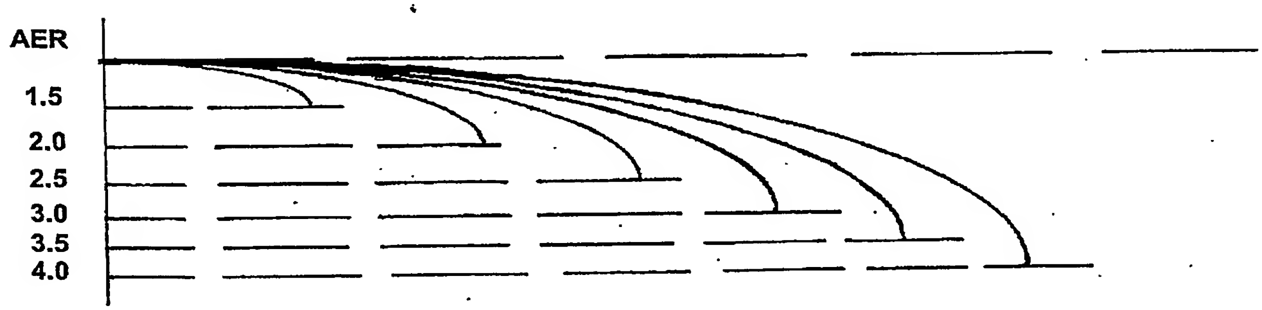


Figure 2



A. Nozzle Diameter, Step Height and AER Fixed



B. Nozzle Diameter and Inlet Swirl Number Fixed

Figure 3

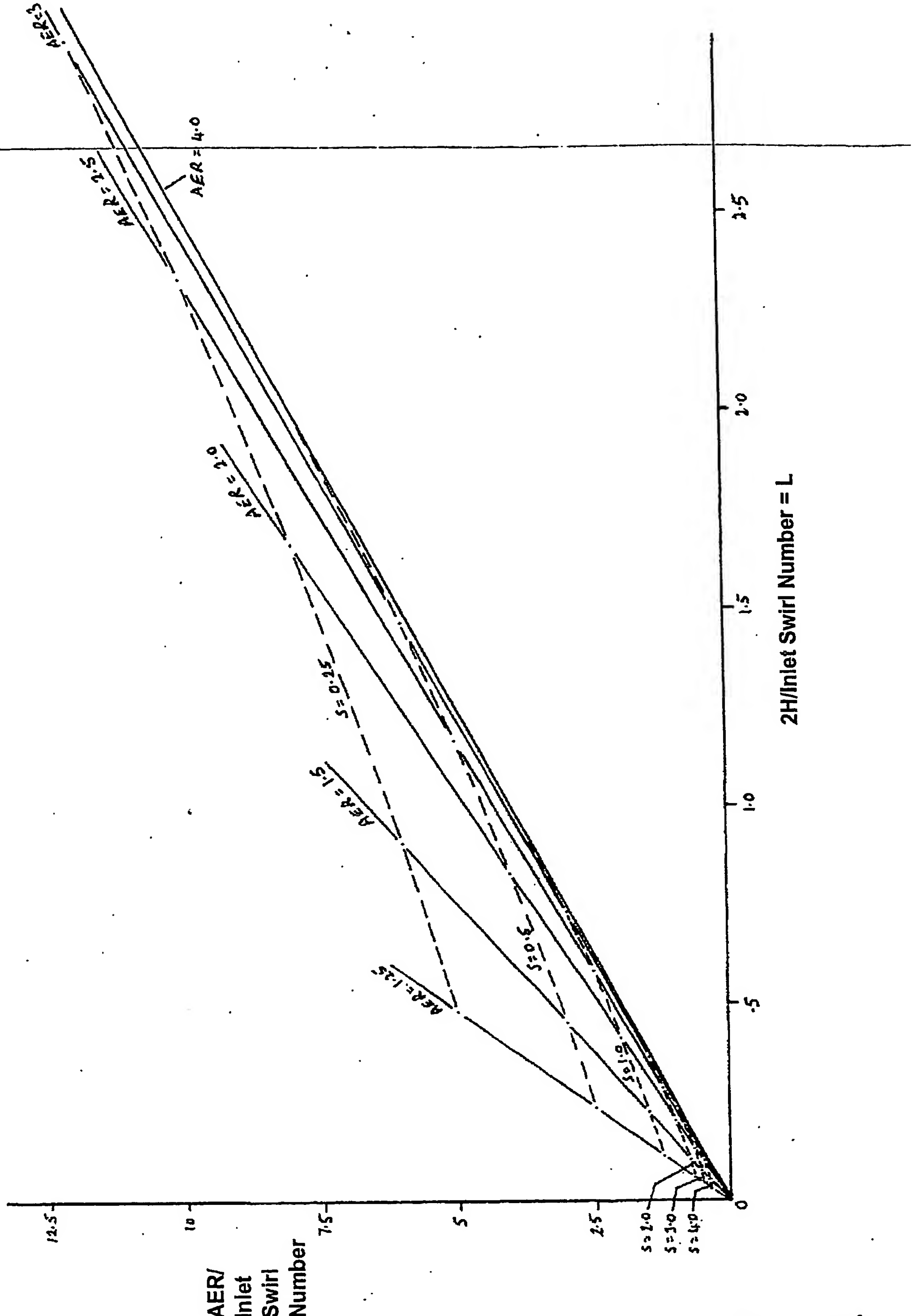
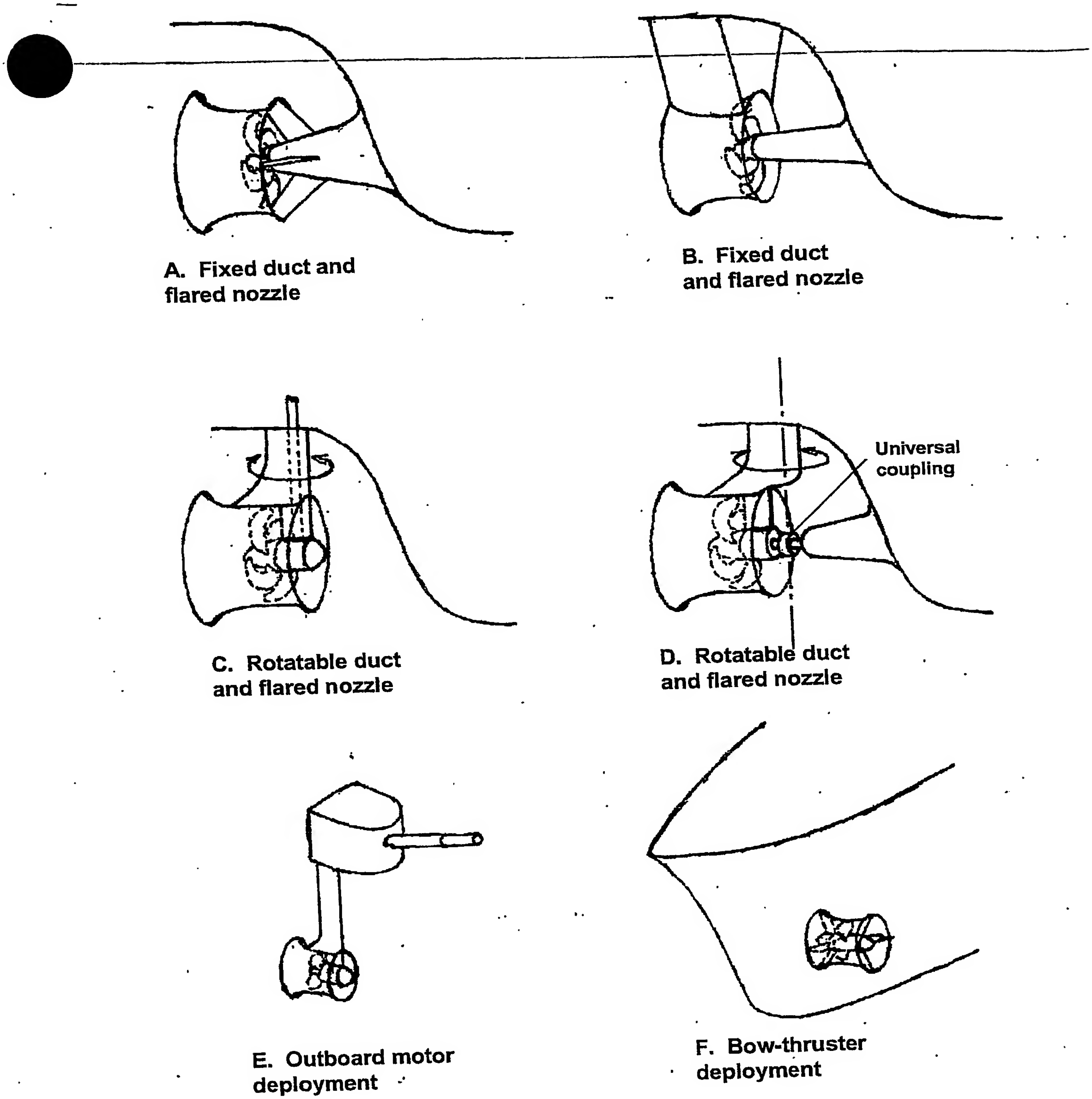

AER/
Inlet
Swirl
Number
12.5
10
7.5
5
2.5
S=2.0
S=3.0
S=4.0
0
.5
1.0
1.5
2.0
2.5
2H/Inlet Swirl Number = L
AER=3
AER=4.0
AER=2.5
AER=2.0
AER=1.5
AER=1.25
S=0.25
S=0.5
S=1.0

Figure 4



A. Fixed duct and flared nozzle

B. Fixed duct and flared nozzle

C. Rotatable duct and flared nozzle

D. Rotatable duct and flared nozzle

E. Outboard motor deployment

F. Bow-thruster deployment

Figure 5

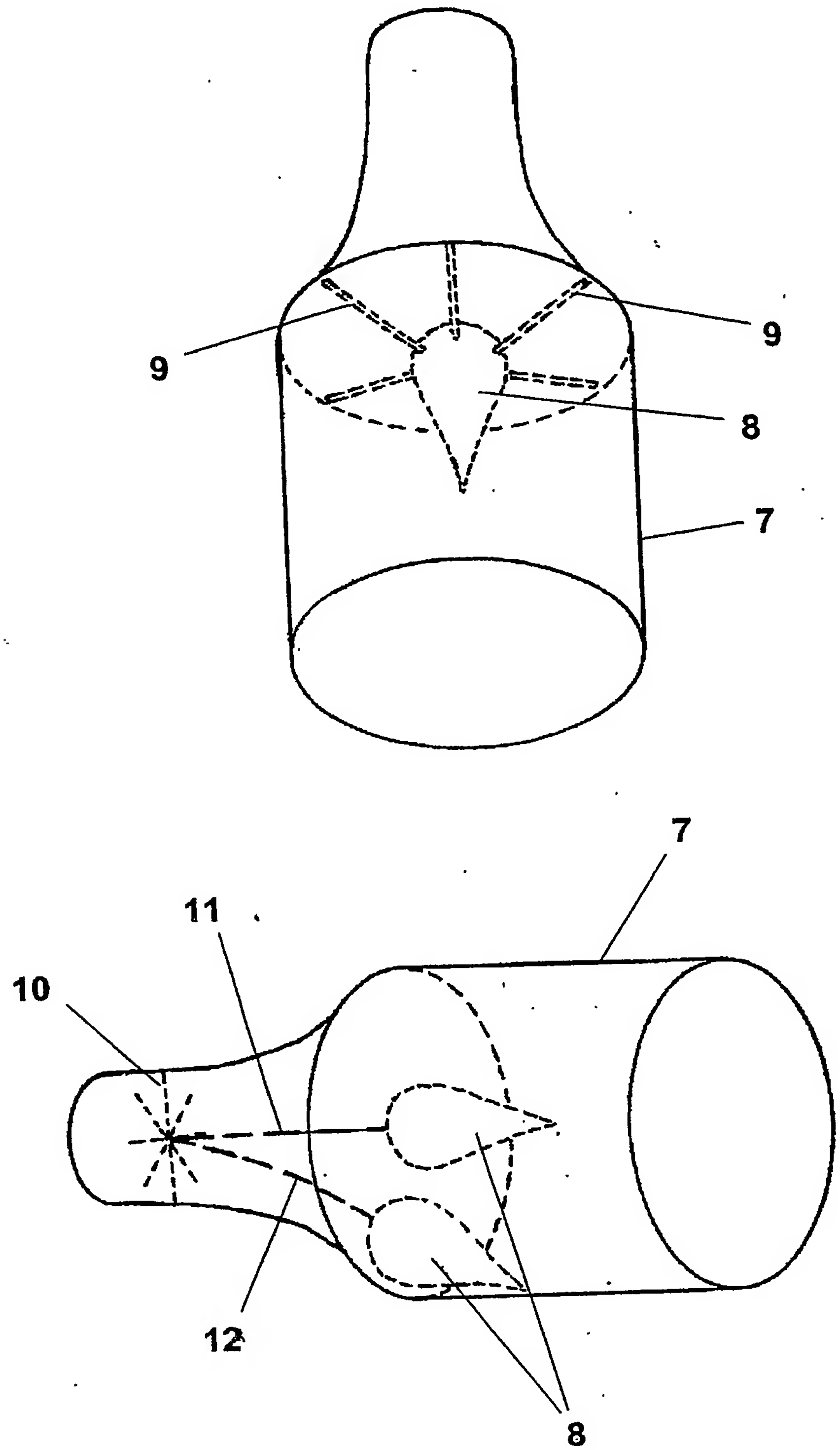


Figure 6

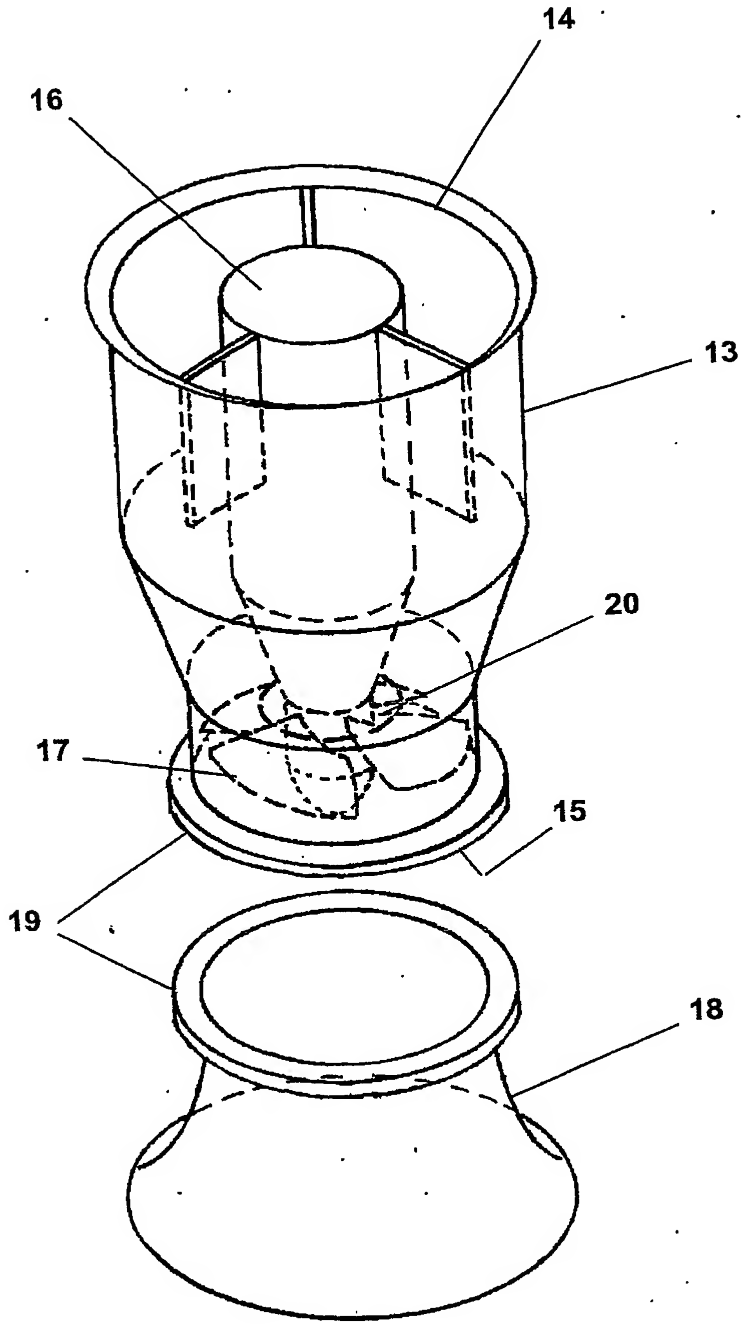
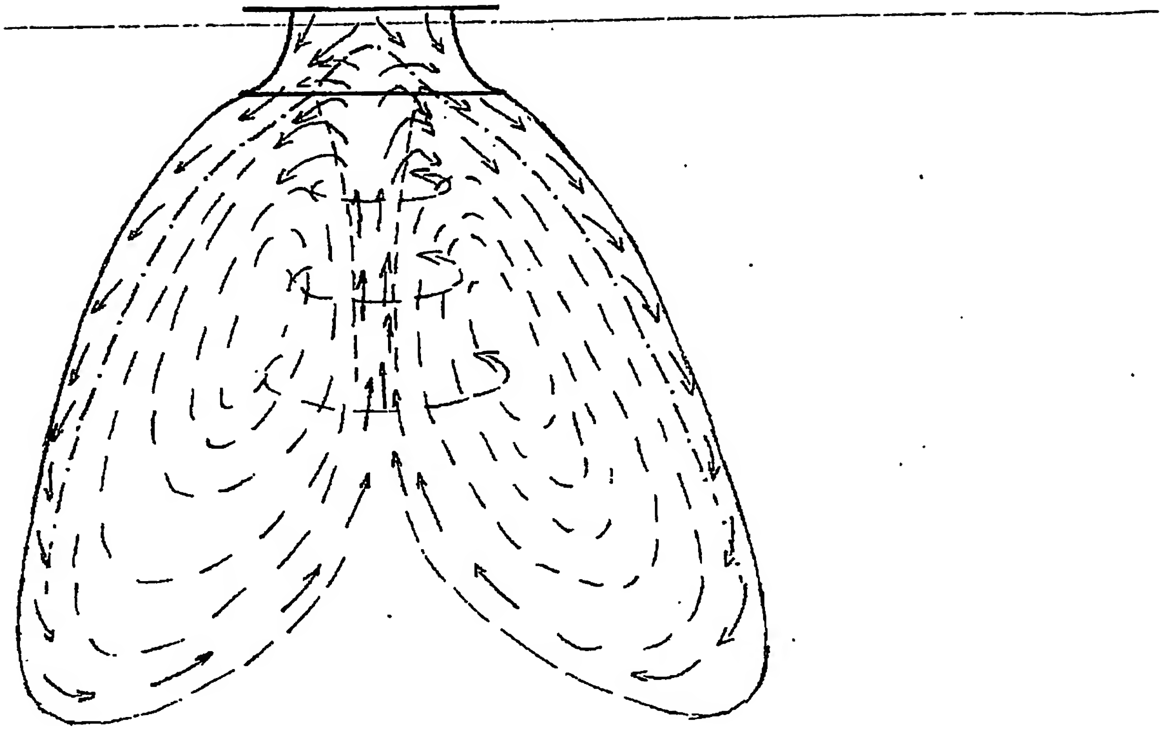


Figure 7

A. Free Jet



B. Impinging Jet

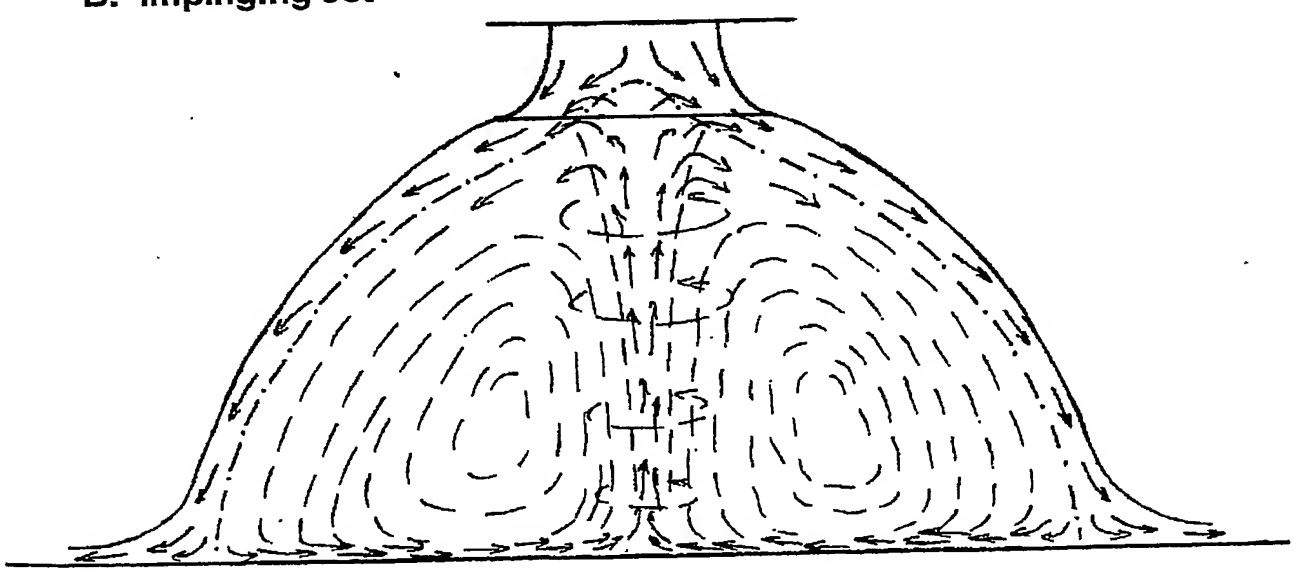


Figure 8

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